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Volcanism in Northwest Ishtar Terra, Venus

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Soviet Venera 15/16 radar images and topographic data for an area in NW Ishtar Terra, Venus (74°N, 313°E) contain evidence for the existence of a complex volcanic center. Located at the intersection of Akna and Freyja Montes (both elevated ~4 to 7 km above the planetary reference radius of 6051 km), this volcanic center has a complex caldera system, possibly more than one major eruptive vent, and associated lava flows at lower elevations. Evidence for a volcanic center at NW Ishtar Terra includes: a smooth-surfaced unit with moderate radar brightness; adjacent (possibly associated) bright flows extending northwestward more than 300 km; an irregularly shaped depression 200 by 250 km in size and ~2.0 km deep; arcuate slopes that appear to mark the rims of several semicircular depressions within the larger depression; and 5.5-km-elevation ridge separating volcanic deposits of northern Lakshmi Planum from those of NW Ishtar Terra. The lack of a notable shield construct at NW Ishtar and the similarity between smooth terrain and undivided plains of Lakshmi Planum suggest that volcanic units at NW Ishtar Terra may represent an earlier (perhaps younger) stage of volcanism than that attributed to Colette and Sacajawea Paterae of Lakshmi Planum. A westward migration in volcanic activity from Sacajawea to Colette to NW Ishtar is supported by relative youth of Colette as compared to Sacajawea, the relatively young stage of volcanism at NW Ishtar Terra, and the superposition of this volcano on the banded terrain of Akna and Freyja Montes.

INTRODUCTION

Volcanism is an important mechanism of surface modification (Phillips and Malin 1983, Wilson and Head 1983, Head and Wilson 1986) and heat transfer on Venus (Solomon and Head 1982). Venusian volcanic landforms are widely distributed and diverse in form, size, and occurrence. Examples of volcanic landforms include: the shields Rhea and Theia Montes of Beta Regio (McGil *et al.* 1981, Campbell *et al.* 1984, Stofan *et al.* 1989); calderas and associated lava flows of Colette and Sacajawea Paterae on southcentral Lakshmi Planum (Magee and Head 1988a, Roberts and Head 1989); volcanic plains of Sedna Planitia (Stofan *et al.* 1987) and Guinevere Planitia (Campbell *et al.* 1989); conical "hills" (believed to be volcanic cones and/or domes) scattered across the rolling plains of northern Venus (Slyuta *et al.* 1988, Aubele *et al.* 1988); and possible pyroclastic deposits of Bell Regio (Barsukov *et al.* 1986), Colette Patera (Magee and Head, 1988b), and Guinevere Planitia (Campbell *et al.* 1989). In addition, the elliptical features called arachnoids (e.g., Stofan and Head 1988) and coronae (or "ovoids") (Barsukov *et al.* 1986, Edmunds *et al.* 1988, Kiefer and Hager 1988, Pronin and Stofan 1988, Stofan *et al.* 1988) are inferred to have origins related to both volcanic and tectonic processes. Recognition of each type of volcanic landform is important for understanding the nature of volcanic processes on Venus, particularly the distribution of volcanism, styles and rates of eruption, and the relationships between volcanism and tectonism.

This paper presents evidence for a pre-

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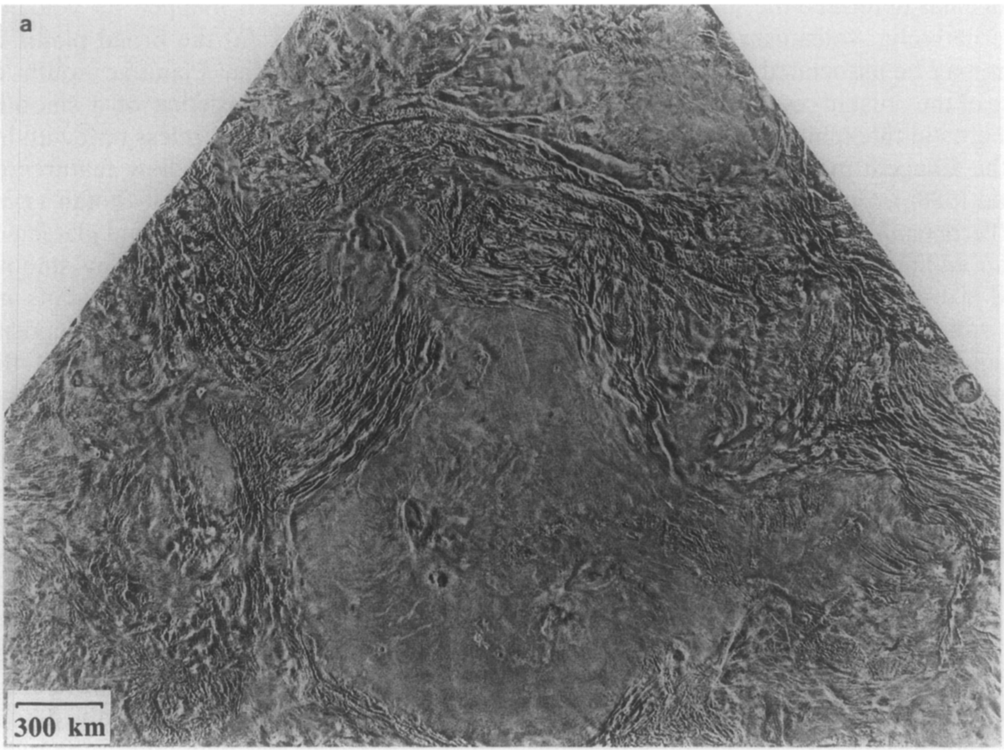
viously undocumented volcanic complex in the highlands of NW Ishtar Terra (74°N, 313°). The proposed volcanic center is in mountainous "banded" terrain thought to have formed by regional compression (e.g., Solomon and Head 1984, Crumpler *et al.* 1986). Its presence must be accounted for in models of tectonic processes of this area. There are three objectives for this analysis of the volcanic complex in NW Ishtar Terra: (1) to document a volcanic origin for this feature; (2) to evaluate its place within the framework of known volcanic landforms of Lakshmi Planum; and (3) to assess the relationships between volcanism and tectonism in this region. Data used include Soviet 15/16 radar images (acquired at an 8-cm wavelength, an incidence angle of 10°, and a resolution of 1 to 3 km) and topography (*Fotokarta Veneri* B-4, 1987).

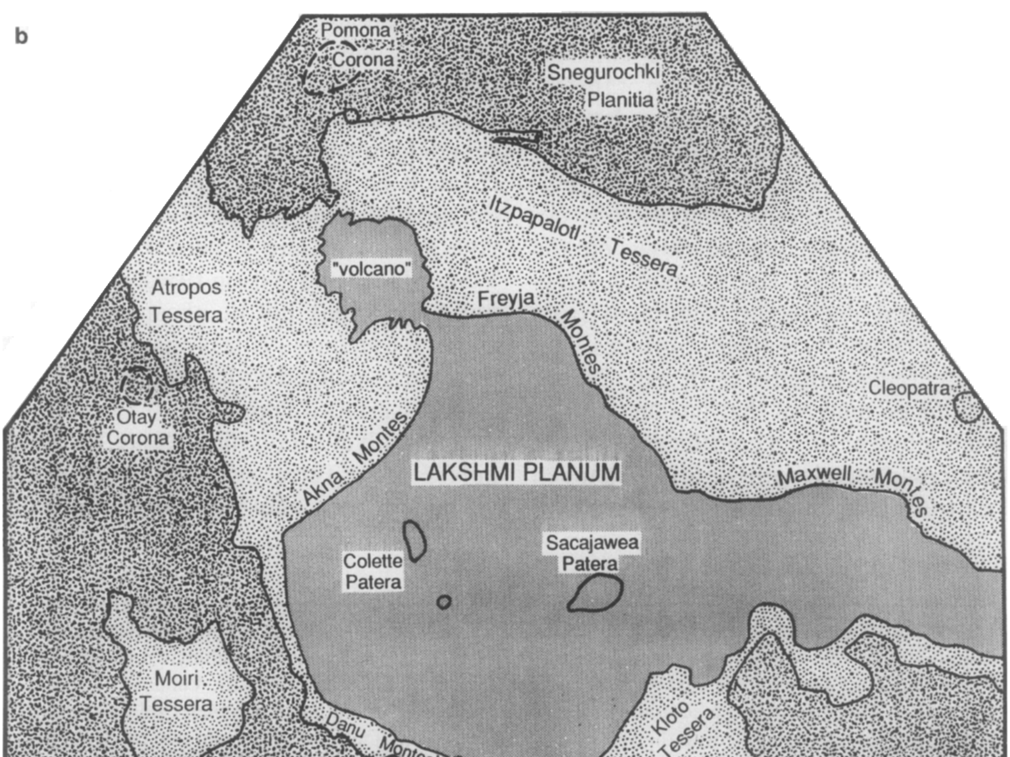
Geologic Setting

Ishtar Terra is the northernmost highland province on Venus (65°N, 350°), and ranges in elevation from about 0.0 to almost 12.0 km above the planetary reference radius of 6051 km (Masursky *et al.* 1980). Ishtar Terra includes the three separable topographic elements of Lakshmi Planum on the west, the central mountains of Maxwell Montes, and the eastern ridged terrain of Fortuna Tessera. This study focuses on northwestern Ishtar Terra, including the highly deformed mountains and Lakshmi Planum. Lakshmi Planum is a smooth-surfaced, elevated (~3 to 5.5 km) plateau bordered by the "ridge-and trough" banded structure of the major mountain belts Akna, Freyja, and Maxwell Montes (Fig. 1). Akna Montes, along the northwestern margin of Lakshmi Planum, trends more than 700 km NE-SW, with elevation up to 7 km (Basilevsky *et al.* 1986). Freyja Montes form the northern and northwestern borders of Lakshmi Planum. The banded terrain of this mountain range also has elevations up to 7 km, with a 400-km long, 150-km wide system of E-W-trending subparallel ridges and grooves north of Lakshmi (Basilevsky *et al.* 1986). On the northeast, the Freyja Montes bend sharply (>90°) to the south and merge with the Maxwell Montes belt, where elevations of nearly 12 km are observed. Analyses of the size, spacing, and orientation of ridges in the mountain ranges bordering Lakshmi Planum support an origin by large-scale compression (e.g., Solomon and Head 1984, Crumpler *et al.* 1986, Head 1988).

A variety of volcanic features are observed on Lakshmi Planum, including the calderas and low shields of Colette (130 × 180 km) and Sacajawea (120 × 200 km) Paterae, their long lava flows (Colette flows average 15 km wide, 100–300 km long; Roberts and Head 1989), and possibly associated smaller vents (e.g., Barsukov *et al.* 1986, Magee and Head 1988a,b, Roberts and Head 1989). Two explanations for the origin of the shields Colette and Sacajawea (and perhaps for the entire plateau) have been offered. First, the summit calderas of Colette and Sacajawea may be the surface expression of Hawaiian-type hot spots (Pronin 1986), in which case the growing volcanic

FIG. 1. (a) Venera 15/16 radar image Lakshmi Planum and vicinity (center at 65°N, 330°), on the Ishtar Terra highland of Venus. Radar image brightness is strongly influenced by slope and surface roughness: slopes oriented toward the radar antenna (east-facing slopes for the west-looking Venera radar) and rough surfaces (at the scale of the radar wavelength) are high-return or bright features; slopes facing away from the radar antenna and smooth surfaces are low-return or dark features. (b) sketch map of major geologic features and units of western Ishtar Terra: the dark-stippled areas mark the surrounding mottled plains (0.0 to 1.0 km elevation); the light-stippled areas represent the rough "ridge-and trough" features of the mountainous terrain (1.0 to 7.0+ km elevation); and the gray areas include the smooth lava plains and volcanic shields of the elevated plateau (3.0 to 5.0+ km elevation; *Fotokarta Veneri B-4*, 1987). North is to the top.


a
300 km


b
Pomona Corona
Snegurochki Planitia
Itzpapalotl Tessera
"volcano"
Atropos Tessera
Freyja Montes
Otay Corona
Cleopatra
Akna Montes
LAKSHMI PLANUM
Maxwell Montes
Colette Patera
Sacajawea Patera
Moiri Tessera
Kloto Tessera
Danu Montes

edifice has deformed the surrounding areas. Alternatively, volcanism at Lakshmi Planum may be associated with melting at the base of the crust in response to convergence and crustal thickening during the formation of the adjacent mountain belts (Magee and Head 1988b). Geologic analyses of NW Ishtar Terra enable us to establish the existence of an additional large volcano in this highland province and to compare its morphology and occurrence to those of Colette and Sacajawea. Although the tectonic environment of the NW Ishtar Terra volcano (located at the junction of two major compressional mountain belts) appears strikingly different from that of Colette and Sacajawea, such comparisons facilitate an understanding of the origin and evolution of volcanism on Ishtar Terra.

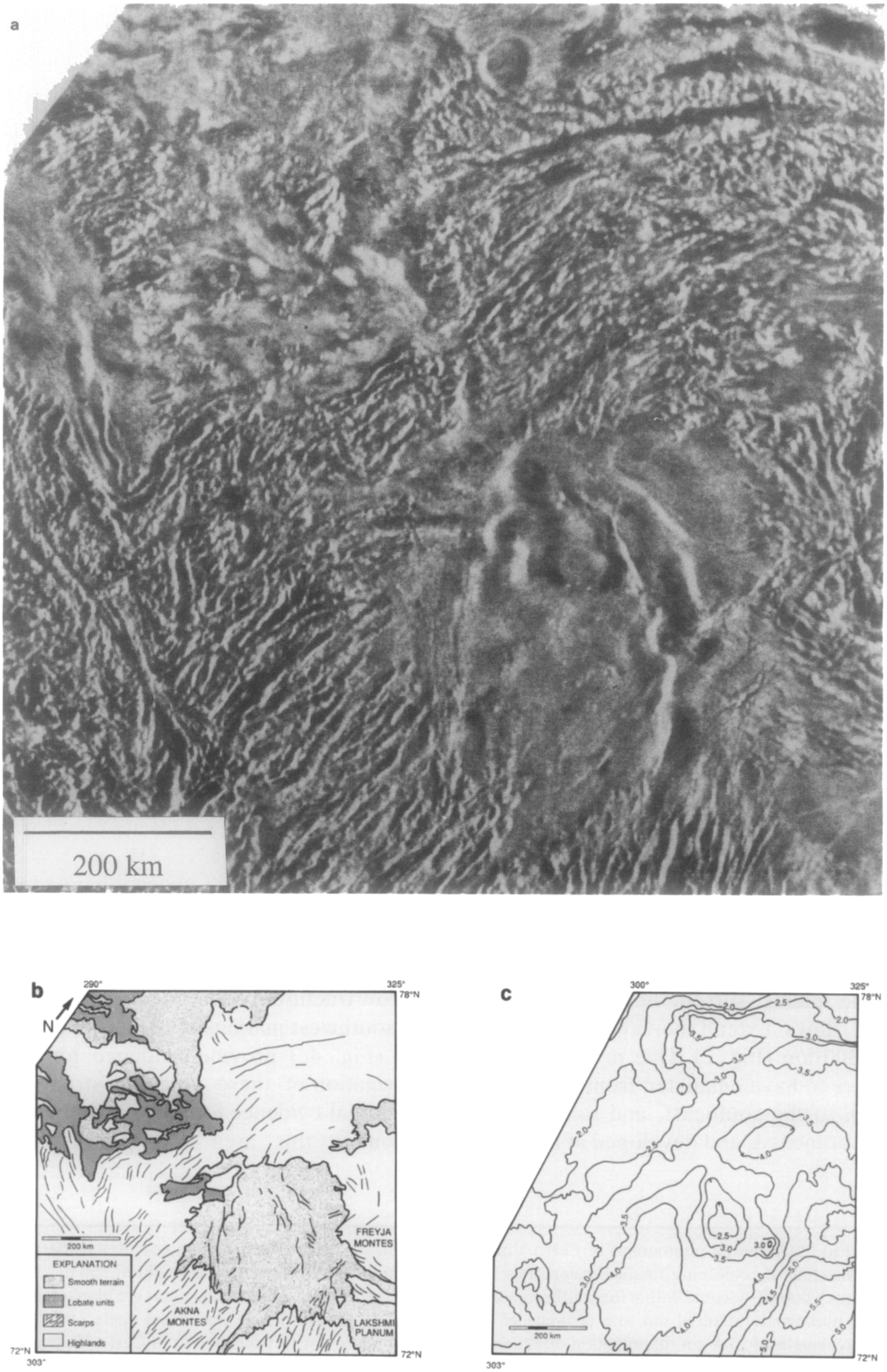
VOLCANISM IN NW ISHTAR TERRA

Soviet Venera 15/16 radar images and topographic data for NW Ishtar Terra contain evidence for a proposed volcanic center superimposed on banded terrain at the intersection of Akna and Freyja Montes (Gaddis and Greeley 1989; Fig. 2). We consider smooth, moderately bright terrain at this intersection to consist of volcanic deposits erupted from vents located within a complex caldera system centered at 74°N, 313° (Fig. 2b). This interpretation is supported by occurrences of bright, lobate flows on the plains to the NW and a large, complex, irregularly shaped depression separated from Lakshmi Planum by a ridge. Surfaces with moderate radar brightness in Fig. 2a are thought to be material that has an average roughness height of ~8 cm (the scale of the Venera radar wavelength) or less (Campbell and Burns 1980). Such surfaces elsewhere on Venus have been mapped as volcanic plains and include: (a) the broad plains of Guinevere and Sedna Planitiae south of Lakshmi Planum, consisting of a smooth-surfaced, relatively featureless unit with little evidence of individual flow features or source vents (Province IV of Stofan *et al.* 1987); (b) portions of the elevated plateau of Lakshmi Planum characterized by smooth plains for which no specific source vents are observed ("distributed effusive" deposits of Roberts and Head 1989); and (c) the widely distributed "smooth plains" of Barsukov *et al.* (1986).

Although localized deposits of smooth terrain are observed in the adjacent banded mountains, no individual lava flows are identified within the smooth terrain of the proposed volcanic center. Their apparent absence may be due to: (a) the limited spatial resolution of the Venera 15/16 radar images (>1 km); (b) flow surfaces which were originally smooth or have been modified to a roughness height less than that of the radar wavelength (~8 cm); or (c) a true absence of flows. Analyses of radar images of terrestrial lava flows show that smooth-surfaced flows (such as pahoehoe flows at Kilauea, Hawaii) can be indistinguishable from surrounding low-return (dark) volcanic deposits such as ash (Gaddis *et al.* 1989). Although both smooth pahoehoe and rough aa lava flow types are expected to occur on Venus (Head and Wilson 1986), smooth-textured flows may not be observable if their average roughness is less than ~8 cm or if they are associated with pyroclastic or other smooth-surfaced deposits

Alternatively, lava flows may be absent in NW Ishtar Terra, suggesting that smooth volcanic terrain may represent explosively

FIG. 2. (a) Venera 15/16 radar image of NW Ishtar Terra, Venus. The radar illumination direction is from the right (east to west). North is to the top. (b) Sketch map of major radargeologic units of NW Ishtar Terra. (c) Topographic data (0.5-km contour intervals) of NW Ishtar Terra, Venus (*Fotokarta Veneri B-4*, 1987). Concentric contours in the center of this figure outline a complex caldera system and a possible associated vent to the southeast. Contours in kilometers above mean planetary radius of 6051 km.

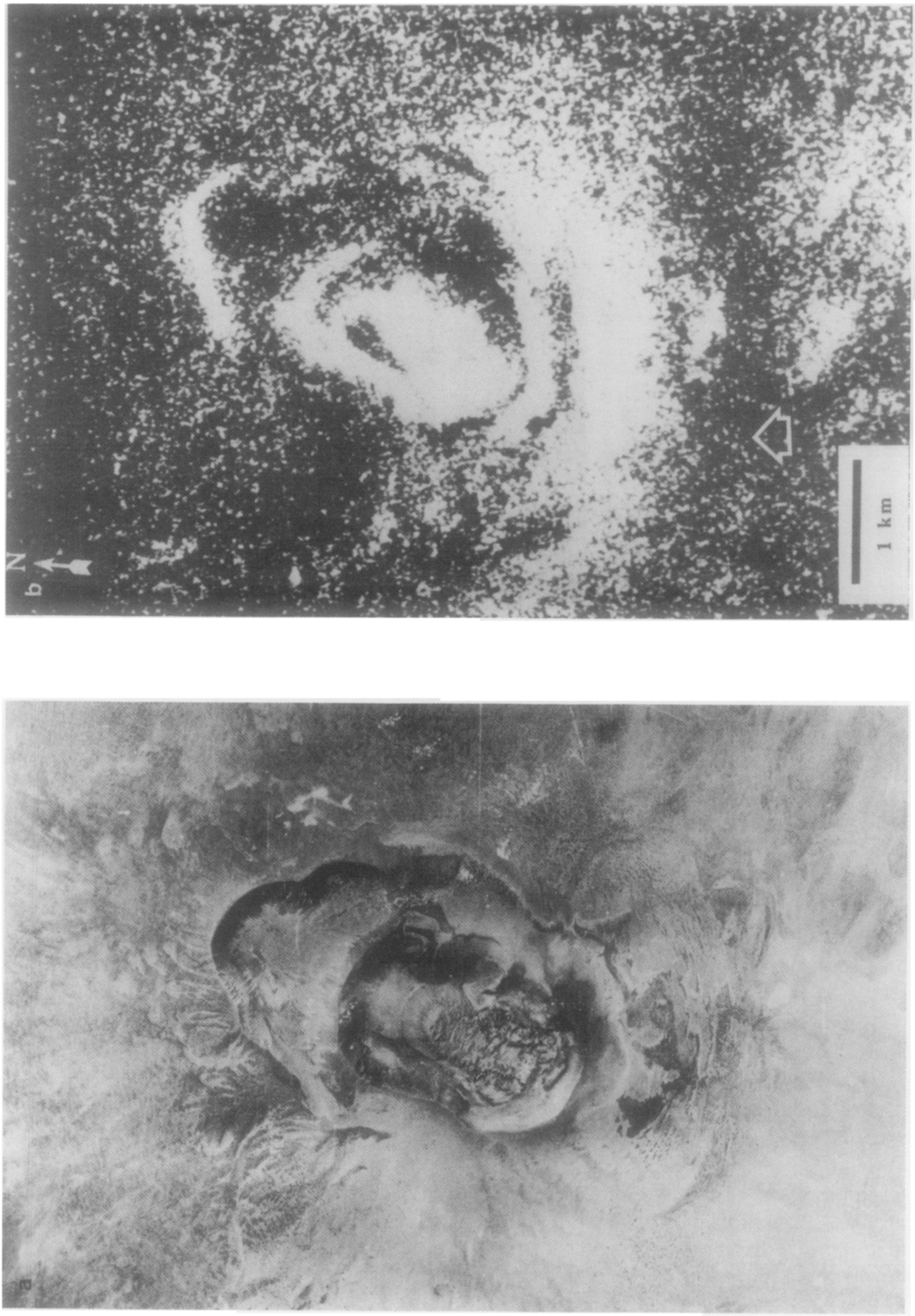

a
200 km
b
290°
325°
78°N
N
200 km
EXPLANATION
Smooth terrain
Lobate units
Scarps
Highlands
FREYJA MONTES
AKNA MONTES
LAKSHMI PLANUM
72°N
303°
72°N
c
300°
325°
78°N
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
200 km
303°
72°N

emplaced material. A terrestrial example of such a volcanic feature is the Cerro Volcan Quemado (Fig. 3), a silicic volcano with a prominent complex caldera, central dome, and pyroclastic halo in the Bolivian Andes (Greeley *et al.* 1987). As illustrated in the SIR-A radar image (Fig. 3b),the coalescing crater rims forming the summit caldera are illuminated as bright, scalloped segments by the north-facing radar. In addition to the south-facing slopes, the rough, blocky dome and rock outcrops in the crater rims contribute to the bright radar returns on this image. By contrast, the pyroclastic mantling deposit on the rim and plains surrounding the volcano produce a low (dark) radar return. The radar signature of Cerro Volcan Quemado is therefore dominated by the crater rim slopes and the halo of fine-grained ash extending more than 7 km. Despite the huge differences in scale, the morphologic similarities between the Cerro Volcan Quemado and the proposed volcano in NW Ishtar Terra suggest that an explosive origin for at least some eruptive products from the latter cannot be ruled out at this time. Although theoretical considerations suggest that unusually high volatile contents (>4 wt%) are required for pyroclastic volcanism to occur on Venus (Head and Wilson 1986), a pyroclastic origin was proposed for numerous smooth, moderately bright deposits (e.g., Barsukov *et al.* 1986, Magee and Head 1988b, Campbell *et al.* 1989).

To the northwest of the volcanic center, on the plains surrounding Ishtar Terra, bright flows extend northwestward more than 300 km (Fig. 2). One prominent flow appears to have emanated from the banded terrain to the southeast, and to have widened, branched, and developed at least four lobes extending several kilometers to the northwest (Figs 2a, 2b). An association between these flows and the large volcanic caldera to the southeast is supported by: (a) proximity to the volcano (~200 km distance); (b) the presence of isolated ponds of smooth terrain within the banded terrain between the bright flows and the volcano; (c) the regional northwestward slope from the volcano (at ~4 km elevation) to the northern plains; (d) the morphology of the flows, suggesting that they originated to the southeast in the direction of the volcano, and flowed and branched out toward the north and west.

The enhancement of radar-facing (eastward) slopes in Fig. 2a also reveals a series of bright, arcuate slopes that appear to mark the rims of several semi-circular topographic depressions. The central region of Fig. 2a is enlarged and shown in Fig. 4, with the radar image (Fig. 4a) and a high-pass filtered version (Fig. 4b) presented for enhancement of radar-facing slopes. The bright/dark pattern of many of the arcuate scarps in these images suggest the presence of several small, overlapping (perhaps nested) depressions or craters within the larger depression (Fig. 4c). The orientation of these arcuate slopes does not conform to those of the dominant NE-SW and NW-SE structural trends in the adjacent banded terrain, indicating that the semi-circular depressions are superimposed on (and therefore were formed after) the banded terrain. Narrow fractures observed on the southeast and southwest margins of the larger depression (Fig. 4c) provide evidence for later deformation of these volcanic structures. Additional evidence for postvolcanic deformation in this area was presented by

FIG. 3. (a) aerial photograph of Cerro Volcan Quemado, a silicic volcano with a complex caldera consisting of coalescing smaller crater rims. It has a 6.5-km basal diameter and a height of 350 m. A blocky dome is located within the southernmost crater, and the rim and surrounding plains are blanketed by pyroclastic material out to a distance of ~7 km. (b) SIR-A radar image (incidence angle of 50°, wavelength of 23.5 cm, illumination direction from bottom shown with wide arrow) of Cerro Volcan Quemado. (from Greeley *et al.* 1987)


b
N
1 km
a

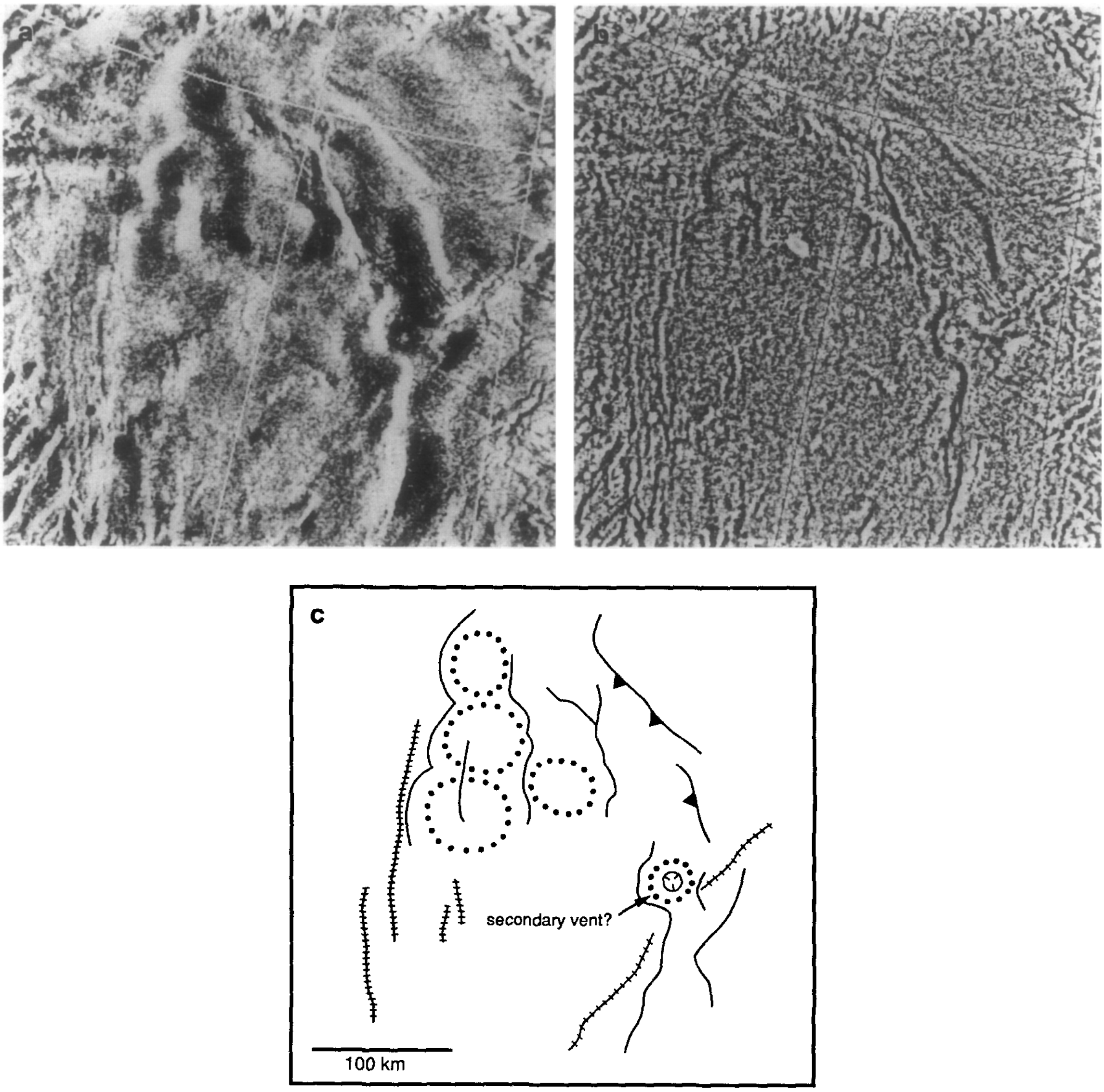


FIG. 4. (a) Venera 15/16 radar image of the complex caldera. (b) high-pass filtered radar image enhancing the bright, east-facing (toward the radar) slopes of the caldera. (c) sketch map of the complex caldera showing arcuate slopes (solid lines) marking overlapping, semi-circular depressions (dotted lines), narrow fractures (hatched lines), and the proposed thrust faults (solid lines with triangles) of Crumpler *et al.* (1986). North is to the top.

Crumpler *et al.* (1986), who interpreted the arcuate scarps forming the eastern boundary of the proposed volcanic center (Fig. 4c) to mark thrust faults formed after the volcanic deposits were emplaced.

The presence of semi-circular depressions forming a complex caldera in this area is supported by the topographic data in Fig. 2c. These data show two concentric descending elevation contours (3.5 to 2.5 km; centered at 74°N, 314° and 73.5°N, 318°) superimposed on the regional slope ranging from about 5.5 km elevation to the SE (toward Lakshmi Planum) to about 2 km elevation to the NW. If the 3.0-km elevation is taken as the outer boundary of a complex caldera structure within the smooth terrain, the structure is 200 by 250 km in size. The smaller depression to the southeast, possibly representing a secondary volcanic source vent, is about 50 km in diameter. Note that a positive-relief construct such as a mound or shield associated with this complex caldera structure cannot be distinguished in these topographic data.

DISCUSSION

The morphology of the volcano in NW Ishtar Terra can be compared to that of Colette and Sacajawea Paterae in southcentral Lakshmi Planum (Fig. 1) for insight into the styles of eruption, origin, and evolution of volcanism on Ishtar Terra. The structural and volcanic features of Colette and Sacajawea have been characterized in detail by Magee and Head (1988a). In broad terms, the apparent caldera in NW Ishtar Terra is comparable to the calderas of Colette and Sacajawea Paterae in that each structure is 1.5 to 2 km deep and consists of a series of discontinuous, curved scarps marking faults along which caldera walls may have collapsed after removal of magma. However, the caldera in NW Ishtar Terra is both more structurally complex (with several possible nested craters and an adjacent small caldera) and larger (200 by 250 km) than that of either Colette (130 by 180 km) or Sacajawea (200 by 120 km).

Magee and Head (1988a) have noted that centralized effusion was the dominant style of volcanism at Colette and Sacajawea, with ~radial flows emanating from near the calderas and overlying the adjacent undivided volcanic plains units. As we have observed, the modes of eruption (effusive vs explosive) and source vents of volcanic products associated with the volcanic center in NW Ishtar Terra are difficult to determine with the Venera data. However, observations of smooth terrain and distal lava flows suggest that the complex caldera was a major locus of volcanism in NW Ishtar Terra. Although the smooth terrain in NW Ishtar Terra may consist of undetectable lava flows or perhaps pyroclastic deposits, it is also possible that smooth terrain may be comparable in form and occurrence to the undivided lava plains of northern Lakshmi Planum (Magee and Head 1988a).

Colette and Sacajawea have been described as shield volcanoes on the basis of their summit calderas and associated lava flows (e.g., Barsukov *et al.* 1986), but their edifice heights (~0.5 to 1.5 km) and flank slopes (<0.3°) are low. Lower edifice heights on Venus may be related to higher temperature gradients (Head and Wilson 1986): magma chambers may be located at shallower depths, producing smaller magma/host rock density contrasts and reducing the forces that drive eruptions on Venus. The eruption and emplacement of long lava flows such as those observed at Colette and Sacajawea should also contribute to lower edifice heights (Head and Wilson 1986). Such evidence, coupled with the absence of a notable shield and observable lava flows in association with the complex caldera in NW Ishtar Terra, suggests that shield-forming volcanism has not occurred in this region.

The lack of shield-forming volcanism and the similarity between smooth terrain and undivided plains of Lakshmi Planum suggest that volcanic units at NW Ishtar Terra may represent an earlier (perhaps younger) stage of volcanism than that attributed to Colette and Sacajawea. Although age relationships for volcanic features on Lakshmi Planum are difficult to establish, the lower relief and subdued appearance of flows and structures at Sacajawea suggest that it is an older volcanic center than Colette (Barsukov *et al.* 1986, Stofan *et al.* Magee and Head 1988a). On the basis of the relative youth of Colette and the apparent synchronicity of volcanic and tectonic processes on western Ishtar Terra, Magee and Head (1988b) proposed an east-to-west migration of volcanism on Lakshmi Planum. A westward migration in volcanic activity from Sacajawea to Colette to NW Ishtar is supported by the relatively young stage of volcanism at NW Ishtar Terra and the superposition of this volcano on the banded terrain of Akna and Freyja Montes.

The tectonic setting of Ishtar Terra has been the subject of intense consideration since Pioneer Venus data first revealed it as a landmass closely resembling a terrestrial continent (e.g., Pettengill *et al.* 1979, Phillips *et al.* 1981). A compressional tectonic origin for Akna, Freyja, and Maxwell Montes is well established (e.g, Phillips *et al.* 1981, Solomon and Head 1984, Crumpler *et al.* 1986). Although a simple hot-spot crustal genesis mechanism is implausible for Ishtar Terra, crustal thickening in response to convergence over a region of mantle downwelling can account for both the compressional deformation and the elevated topography of Ishtar (e.g., Morgan and Phillips 1983, Banerdt 1986, Kiefer and Hager 1989). As part of this scenario, lithospheric delamination may contribute to localized melting of the crust beneath Lakshmi Planum (e.g., Kiefer and Hager 1990, Grimm and Phillips 1990). In any case, it seems likely that volcanism on Ishtar Terra is attributable to basal melting of a thickened crust.

Although the exact relationship of volcanism and tectonism in Ishtar Terra has yet to be established (e.g., Roberts and Head 1990), a plausible scenario would include: overlapping occurrences of compression and crustal thickening; fracturing and possible imbrication and/or underthrusting of portions of the crust; and basal melting and episodic volcanism. The almost perpendicular intersection of the highly banded terrain of Akna and Freyja Montes was no doubt the focus of intensive local deformation and would thus be a likely site for volcanism. Although Lakshmi Planum is surrounded on all sides by highly deformed terrains (Fig. 1), no other probable volcano is observed in such close association with deformation. The intersection of the Akna and Freyja Montes is bordered to the southeast by Lakshmi Planum and to the northwest by much less deformed volcanic plains. Thus, the apparent uniqueness of the volcano in NW Ishtar Terra may be attributable to the combined influence of intense compression and crustal fracturing at this intersection and the lack of additional, possibly inhibiting, tectonic influences in the vicinity. Alternatively, volcanic plains in areas such as southeastern Lakshmi Planum (southwest of Maxwell Montes) may be the remnants of previous volcanic centers. Thus both deformation and volcanism may have migrated westward in Ishtar Terra.

SUMMARY AND CONCLUSION

NW Ishtar Terra is the site of a volcanic center with a complex caldera structure, possibly more than one eruptive vent, and associated lobed flows at lower elevations. Three characteristics of NW Ishtar Terra support a volcanic origin for this feature: (1) the smooth-textured surface that embays the surrounding terrain; (2) the adjacent, possibly associated bright lobate flows to the northwest; and (3) the large topographic depression and possible nested depressions revealed by radar image brightness and topographic variations, the lack of conformity between the scarps of the "patera" and the surrounding terrain, and the presence of a ridge separating volcanic deposits of Lakshmi Planum from those of NW Ishtar Terra.

In broad terms, the morphology of the complex caldera of NW Ishtar Terra is similar to that of Colette and Sacajawea Paterae, but it is both structurally more complex and larger (~200 by 250 km) than that of Colette (130 by 180 km) or Sacajawea (200 by 120 km). The lack of a notable shield and the similarity of smooth terrain and undivided plains of Lakshmi Planum suggest that volcanic units at NW Ishtar Terra may represent an earlier (perhaps younger) stage of volcanism than that attributed to Colette and Sacajawea. A westward migration in volcanic activity from Sacajawea to Colette to NW Ishtar is supported by relative youth of Colette as compared to Sacajawea, the relatively young stage of volcanism at NW Ishtar Terra, and the superposition of this volcano on the banded terrain of Akna and Freyja Montes.

The location of this volcanic center at the intersection of two mountain belts supports a close association between compressional deformation, crustal fracturing, and volcanism in Ishtar Terra. The apparent uniqueness of the volcano in NW Ishtar Terra may be attributed to both intense localized deformation and the lack of additional tectonic influences that might have acted to inhibit volcanism in this region. Alternatively, apparent volcanic plains in areas such as southeastern Lakshmi Planum (just southwest of Maxwell Montes) may be the remnants of previous volcanic centers, and both deformation and volcanism have migrated westward in Ishtar Terra.

Radar and altimetric data from the Magellan experiment will permit several aspects of this research to be addressed in more detail. High-resolution (<300 m) images will enable us to constrain the nature of volcanic deposits in NW Ishtar and perhaps to identify individual lava flows and source vents. The relationship of the apparently isolated deposits of volcanic materials within the adjacent banded terrain and the large volcanic center can also be evaluated with these data. Combined with topographic information from Magellan, these images can be used to map in detail the structural relationships within the complex caldera. As applied to Colette, Sacajawea, and other volcanic features of Lakshmi Planum, the Magellan data will facilitate an assessment of the age relationships of the Ishtar Terra volcanoes and thus help to constrain the origin and evolution of volcanism in this region.

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